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Improved Voltage Vector Sequences on Model Predictive Control for a Grid Connected Three Phase Voltage Source Inverter

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Abstract

In this paper, improved voltage vector sequences on model predictive control is proposed for a grid connected three-phase voltage source inverter. Two adjacent voltage vectors and zero voltage vectors are utilized in one switching period. Optimal duty cycles for all sectors are calculated. Voltage vector pair with minimum value of the cost function is selected and applied in the next switching period. Voltage vector sequences are arranged similar to the swing patterns generated by the space vector PWM. Thus, minimum number of switching transition and even loss distribution can be achieved. Computer simulation is carried out to validate viablity of the proposed method . The simulation results confirm that the proposed MPC has superior performance compared to the convention MPC.

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Keywords: Model Predictive Control; Voltage Source Inverter; Voltage Vector Sequences

1. Introduction

In the past decade, inverters have played an important role in modern industries. They have become indispensable for a myriad of applications, for instance adjustable speed drives, grid connected inverters and uninterruptible power supply. A great number of control techniques have been presented for controlling the inverter currents.[1-4] For example, hysteresis control is a nonlinear control method that turns switches on/off to regulate the inverter currents

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that reside in hysteresis bands. Linear PI controllers with modulators regulate the inverter currents equal to the reference values by generating the control commands for modulators to produce appropriate output voltages applied to loads. In sliding mode control, suitable sliding surfaces are selected to force the inverter currents to follow a desired trajectory [2]. Deadbeat control is a class of predictive control [3]. It uses known models to calculate output voltages that make zero errors in one sampling period.

Model predictive control MPC extends the concept of deadbeat control [4]. It provides more flexible criteria that are expressed as cost functions to be minimized. In particular for a finite set MPC with predictive horizon $N = 1$, it is simple, intuitive, and suitable for application of three-phase inverters. However, the conventional MPC may suffer from computational burdens and require high switching frequency.

This paper presents improved voltage vector sequences on model predictive control for three-phase voltage source inverter. Two adjacent voltage vectors and zero voltage vector are utilized in one switching period. The cost functions in terms of the current errors in $\alpha\beta$ frame are formulated. Analytical solutions of optimal duty cycles for all sectors are derived. The proposed voltage vector sequences minimize the number of switching transisitions. The proposed method is validated by computer simulation and its performance is compared to the conventional MPC.

2. Conventional MPC

A three-phase voltage source inverter circuit is shown in Fig. 1. Each leg of a three-phase inverter consists of two IGBT switches which are connected in series. The upper and lower switches of the same leg cannot be turned on at the same time. Thus, a three-phase inverter can generate 6 active vectors and 2 zero vectors in the vector space as shown in Fig. 2. All possible voltage vectors can be expressed in the vector space definition by eq (1) as given in Table 1. Likewise, the load currents can be transformed into $\alpha\beta$ frame by eq (2)

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \qquad \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & -\sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{1}$$

The load currents dynamic for each phase in $\alpha\beta$ frame are expressed as,

$$V_\alpha = L\frac{di_\alpha}{dt} + Ri_\alpha + E_\alpha \qquad V_\beta = L\frac{di_\beta}{dt} + Ri_\beta + E_\beta \tag{2}$$

where L is the filter inductance, R is the filter resistance, $v_{\alpha\beta}$ and $e_{\alpha\beta}$ are the inverter voltage and the grid voltage in $\alpha\beta$ frame respectively. Using the forward Euler approximation, the future load currents in the $\alpha\beta$ frame can be derived in the discrete-time domain as,

$$i^P_{\alpha(k+1)} = i_{\alpha(k)} + \frac{T}{L}(v_{\alpha(k)} - Ri_{\alpha(k)} - e_{\alpha(k)}) \qquad i^P_{\beta(k+1)} = i_{\beta(k)} + \frac{T}{L}(v_{\beta(k)} - Ri_{\beta(k)} - e_{\beta(k)}) \tag{3}$$

In the conventional MPC method, the future current behaviors generated by the corresponding seven voltage vectors can be predicted by the load current dynamics (3). Then, the cost functions are determined in terms of the quadratic error which is defined in eq (4).

$$g = (i^*_{\alpha(k+1)} - i^P_{\alpha(k+1)})^2 + (i^*_{\beta(k+1)} - i^P_{\beta(k+1)})^2 \tag{4}$$

A voltage vector which yields minimum value of the cost function is selected and it will be applied in the next sampling period.

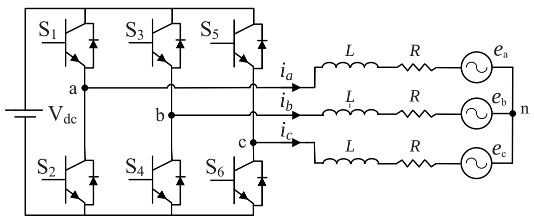

Fig. 1 Three-phase VSI configuration

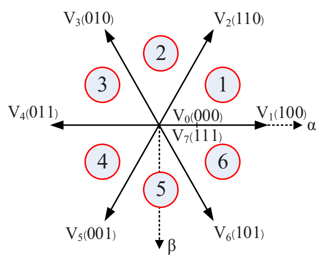

Fig. 2 Eight voltage vectors generated by VSI

Table 1 Voltage vectors in *abc* frame and *αβ* frame

Type		Active vectors						Zero vectors	
		V_1 (100)	V_2 (110)	V_3 (010)	V_4 (011)	V_5 (001)	V_6 (101)	V_0 (000)	V_7 (111)
abc	V_a	2/3Vdc	1/3Vdc	-1/3Vdc	-2/3Vdc	-1/3Vdc	1/3Vdc	0	0
	V_b	-1/3Vdc	1/3Vdc	2/3Vdc	1/3Vdc	-1/3Vdc	-2/3Vdc	0	0
	V_c	-1/3Vdc	-2/3Vdc	-1/3Vdc	1/3Vdc	2/3Vdc	1/3Vdc	0	0
αβ	$V\alpha$	2/3Vdc	1/3Vdc	-1/3Vdc	-2/3Vdc	-1/3Vdc	1/3Vdc	0	0
	V_β	0	√3/3Vdc	√3/3Vdc	0	-√3/3Vdc	-√3/3Vdc	0	0

3. Propose MPC with Improved Voltage Vector Sequences

To further improve quality of the output currents and reduce switching frequency, the new voltage vector sequences are proposed. Instead of applying only one optimal voltage vector, two optimal adjacent voltage vectors along with zero vectors are utilized in the same switching period. Optimal duty cycles for pairs of adjacent two voltage vectors are derived from partial derivatives of the cost functions. The cost functions in *αβ* frame are expressed as,

$$g_{(X)} = (i^*_{\alpha(k+1)} - i^P_{\alpha(k+1)})^2 + (i^*_{\beta(k+1)} - i^P_{\beta(k+1)})^2 \tag{5}$$

$$i^P_{\alpha(k+1)} = i_{\alpha(k)} + \Delta i^P_{\alpha V(x)} d_{(X)} + \Delta i^P_{\alpha V(x+1)} d_{(X+1)} + \Delta i^P_{\alpha V0}(1 - d_{(X)} - d_{(X+1)}) \tag{6}$$

$$i^P_{\beta(k+1)} = i_{\beta(k)} + \Delta i^P_{\beta V(x)} d_{(X)} + \Delta i^P_{\beta V(x+1)} d_{(X+1)} + \Delta i^P_{\beta V0}(1 - d_{(X)} - d_{(X+1)}) \tag{7}$$

$$\Delta i^P_{\alpha V(x)} = \frac{T}{L}(v_{\alpha(k)} - R i_{\alpha(k)} - e_{\alpha(k)}) \qquad \Delta i^P_{\beta V(x)} = \frac{T}{L}(v_{\beta(k)} - R i_{\beta(k)} - e_{\beta(k)}) \tag{8}$$

whereas $d_{(X)}$ and $d_{(X+1)}$ are duty cycles of the two adjacent voltage vectors $V_{(X)}$ and $V_{(X+1)}$ respectively and X is the sector number.

$$\begin{bmatrix} d_{(X)} \\ d_{(X+1)} \end{bmatrix} = \frac{1}{B_\beta C_\alpha - B_\alpha C_\beta} \begin{bmatrix} C_\alpha & -C_\beta \\ -B_\alpha & B_\beta \end{bmatrix} \begin{bmatrix} A_\beta \\ A_\alpha \end{bmatrix} \tag{9}$$

$$A_\alpha = i^*_{\alpha(k+1)} - i_{\alpha(k)} - \Delta i^P_{\alpha V0} \qquad A_\beta = i^*_{\beta(k+1)} - i_{\beta(k)} - \Delta i^P_{\beta V0} \tag{10}$$

$$B_\alpha = \Delta i^P_{\alpha V(X)} - \Delta i^P_{\alpha V0}, \qquad B_\beta = \Delta i^P_{\beta V(X)} - \Delta i^P_{\beta V0} \tag{11}$$

$$C_\alpha = \Delta i^P_{\alpha V(X+1)} - \Delta i^P_{\alpha V0} \qquad C_\beta = \Delta i^P_{\beta V(X+1)} - \Delta i^P_{\beta V0} \tag{12}$$

After the cost functions $g_{(x)}$ are calculated for all sectors, two adjacent voltage vectors with minimum value of the cost function are selected and utilized in the next switching period. Voltage vector sequences are arranged to minimize the number of switching and evenly distribute loss. The rules are summarized as,

1) If the sector number X is odd, the voltage vector sequences follow the pattern $\{V_{(0)}, V_{(X)}, V_{(X+1)}, V_{(7)}\}$ in the first half switching period and repeat in the reverse order in the following half period.
2) If the sector number X is even, the voltage vector sequences follow the pattern $\{V_{(0)}, V_{(X+1)}, V_{(X)}, V_{(7)}\}$ in the first half switching period and repeat in the reverse order in the following half period.

The proposed voltage vector sequences are illustrated in Fig. 3 and 4 for the sector number 1 and 2 respectively.

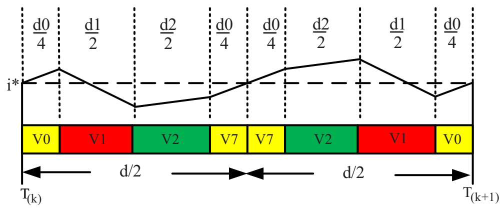

Fig. 3 Voltage vector sequence for odd sectors

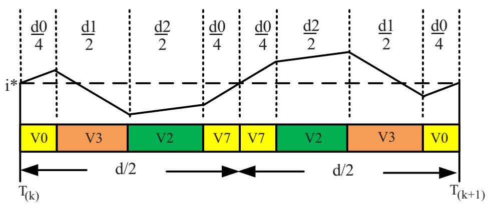

Fig. 4 Voltage vector sequence for even sectors

4. Simulation Results

Simulation of a grid connected three-phase voltage source inverter controlled by the proposed MPC is carried out with PSIM 10 to compare the performance with the conventional MPC. Simulation parameters are given in Table 2.

Table 2 Simulation parameters

Parameters	Values
Resistor	0.2 Ω
Inductor	8m H
DC voltage	200 V
Grid voltage	70 V
Output frequency	50 Hz
Switching frequency	10 kHz

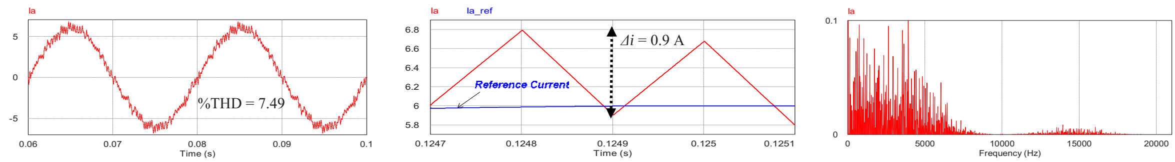

Fig. 5 Current waveform with conventional MPC

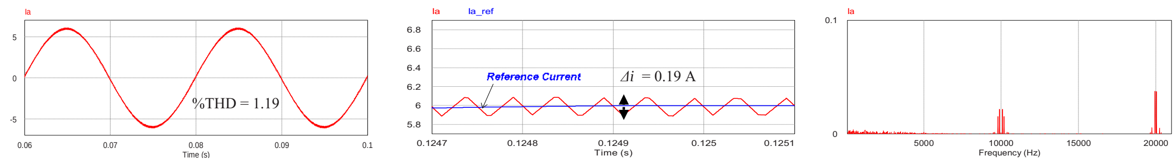

Fig. 6 Current waveform with proposed MPC

Fig. 5 shows the current waveform obtained from the convention MPC. Since only one voltage vector is applied during one switching period, high frequency ripple current is noticeably observed. The percentage of the total harmonic current distortion THD is 7.49%. Frequency spectrum of the current spreads over a wide range of frequency. Fig. 6 shows the current waveform with the proposed voltage vector sequences. The percentage of the THD is 1.19% which is significantly less than that of the conventional MPC. It is observed that the frequency spectrum is concentrated and centered near the switching frequency and its multiples

5. Conclusion

The improved voltage vector sequences on model predictive control for a three-phase voltage source inverter is proposed. As opposed to the conventional MPC, two adjacent voltage vectors and zero voltage vectors are utilized in one switching period. Optimal duty cycles are derived from partial derivatives of the cost functions and provided in a matrix form. Voltage vector sequences are arranged such that a minimum number of switching transisitions and even loss distribution can be achieved. The improved voltage vector sequences on MPC are validated by computer simulation. The simulation results confirm that the proposed MPC has superior performance compared to the convention MPC

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